

PROPER MOTION AND TIMING OF TWO UNUSUAL PULSARS: CALVERA AND 1E 1207.4–5209

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ABSTRACT

Using pairs of images from the *Chandra* High Resolution Camera we examine the proper motion of the central compact object (CCO) 1E 1207.4–5209 in the supernova remnant (SNR) PKS 1209–51/52, and the unusual pulsar Calvera that is possibly a CCO descendant. For 1E 1207.4–5209, an insignificant proper motion of $\mu = 15 \pm 7$ mas yr^{−1} is measured, corresponding to a corrected tangential velocity of $v_{\perp,c} < 180$ km s^{−1} at the distance of 2 kpc. This proves that the previously noted large offset of the pulsar from the apparent geometric center of the SNR is not due to high proper motion; evidently the symmetry of the remnant does not indicate its center of expansion. Calvera has a marginally significant proper motion of $\mu = 69 \pm 26$ mas yr^{−1}, corresponding to $v_{\perp,c} = 86 \pm 33$ km s^{−1} for a hypothetical distance of 0.3 kpc. Notably, its vector is away from the Galactic plane, although its high Galactic latitude of $b = +37^\circ$ may be more a consequence of its proximity than its velocity. We also provide updated timing solutions for each pulsar. Spanning 14.5 yr, the ephemeris of 1E 1207.4–5209 has a small and steady frequency derivative that, because of the negligible proper motion, requires no kinematic correction. The derived surface dipole magnetic field strength of 1E 1207.4–5209 thus remains $B_s = 9.8 \times 10^{10}$ G. Calvera has $B_s = 4.4 \times 10^{11}$ G, intermediate between those of ordinary young pulsars and CCOs, suggesting that it may be on a trajectory of field growth that could account for the absence of descendants in the neighborhood of CCOs in the $P - \dot{P}$ diagram.

Subject headings: pulsars: individual (Calvera, 1E 1207.4–5209) — stars: neutron

1. INTRODUCTION

The group of about ten central compact objects (CCOs) in supernova remnants (SNRs) are defined by their steady thermal X-ray emission, which is their only observational manifestation. Three CCOs have measured spin periods and spin-down rates, indicating that they are weakly magnetized neutron stars (NSs) with dipole fields in the range $3 \times 10^{10} - 10^{11}$ G (Gotthelf et al. 2013a) and negligible spin-down power in comparison with their bolometric X-ray luminosities of $10^{33} - 10^{34}$ erg s^{−1}. Those CCOs that are as-yet unpulsed have the same general spectral properties as the CCO pulsars, strongly suggesting that they are a uniform class. These $10^3 - 10^4$ yr old NSs must represent a significant fraction of NS births. See Gotthelf et al. (2013a) for a review of CCO properties and theories.

Hot regions with different temperatures and areas on the NS surface are deduced from the X-ray spectra and, where available, pulse profiles of CCOs. Paradoxically, such nonuniform surface temperature appears to require strong crustal magnetic fields, much stronger than the external dipole, to channel heat conduction. The evolution of CCOs after their SNRs dissipate is a subject plagued by significant unknowns, primarily because their immediate descendants are not yet evident in existing surveys (Kaspi 2010; Gotthelf et al. 2013b). These factors support theories in which the intrinsic magnetic fields of CCOs are the same as those of ordinary pulsars, but their surface fields change dramatically in time, as will be discussed below.

In this paper, we present additional X-ray studies of one CCO, 1E 1207.4–5209 (also known as PSR J1210–5226), and the unusual NS Calvera, which

may be related to CCOs in evolutionary theories. This work involves proper motion measurements and timing using archival and newly obtained X-ray observations of these two pulsars, designed to address questions of their origin, age, and location.

2. CALVERA

The NS candidate 1RXS J141256.0+792204, dubbed “Calvera,” was discovered in the *ROSAT* All-Sky Survey and first studied with *Chandra* by Rutledge et al. (2008) and Shevchuk et al. (2009). Using *XMM-Newton*, Zane et al. (2011) revealed 59 ms pulsations from Calvera. It is apparently radio quiet despite deep searches for pulsations at the known period (Hessels et al. 2007; Zane et al. 2011). We recently made X-ray measurements of the spin-down of Calvera (Halpern et al. 2013), which showed that, unlike the CCOs, this pulsar is quite energetic, with spin-down power $\dot{E} = 6 \times 10^{35}$ erg s^{−1} and characteristic age $\tau_c = P/2\dot{P} = 2.9 \times 10^5$ yr.

Calvera’s place among the families of NSs is unclear, in part because its distance and luminosity are highly uncertain. Its apparently thermal X-ray emission can be modeled to place a rough upper limit of $d < 2$ kpc for a typical NS surface area (Zane et al. 2011; Halpern et al. 2013), although as a “young” pulsar at high Galactic latitude, $b = +37^\circ$, it may be ~ 10 times closer than that. Given its energetics, it is somewhat surprising that no γ -rays have been detected from Calvera by the *Fermi* Large Area Telescope. Halpern et al. (2013) derived a γ -ray upper limit that is at least 2 orders of magnitude below the typical γ -ray luminosities of pulsars of comparable \dot{E} .

Calvera is of special interest as a candidate for the elu-

TABLE 1
LOG OF *Chandra* HRC-I OBSERVATIONS

ObsID	Date (UT)	Exposure (ks)	Roll Angle (°)	Reference Source Radius (")	Source Counts	Pulsar Radius (")	Counts
Calvera							
8508	2007 Feb 18	2.14	116.00	1.5	8	1.5	188
15806	2014 Apr 2	29.96	157.88	1.5	175	2.5	2819
1E 1207.4–5209							
4593	2003 Dec 28	49.71	71.72	3.0	301	2.5	11636
15291	2013 Dec 18	35.88	80.03	3.0	183	2.5	8432

sive descendants of CCOs, missing in the sense that there are so few pulsars in the immediate neighborhood of the CCOs in the $P - \dot{P}$ diagram. This is why a leading theory for CCOs involves burial of a typical NS magnetic field ($\sim 10^{12}$ G) by prompt fall-back of a small amount of supernova ejecta, followed by diffusive regrowth of the same field on a time scale of $\sim 10^4$ yr (Ho 2011; Viganò & Pons 2012; Bernal et al. 2013). In this picture, Calvera could have been a CCO that evolved upward along a vertical track in the $P - \dot{P}$ diagram (increasing \dot{P}), to the point where its current surface dipole magnetic field, $B_s = 4.4 \times 10^{11}$ G, is approaching those of “ordinary” young pulsars (see Figure 1 of Halpern et al. 2013).

In order to further investigate the origin, distance, and evolution of Calvera, we obtained a second-epoch observation with the *Chandra* High Resolution Camera to measure its proper motion. The results of that analysis are reported here.

2.1. X-ray Observations

Calvera was first observed by *Chandra* on 2007 February 18 for 2.1 ks using the High Resolution Camera for Imaging (HRC-I) in order to eliminate possible optical counterparts (Rutledge et al. 2008). We obtained a second, 30 ks HRC-I observation of Calvera on 2014 April 2 to measure its proper motion and refine its spin-down rate. Observational details are given in Table 1. The HRC-I detector provides sub-arcsecond astrometry and millisecond timing over a 0.2–12 keV bandpass, weighted toward the lower energies, with little or no spectral resolution. A wiring error in the HRC-I that causes typical errors of 4 ms in the photon arrival times¹ does not significantly impact the timing of the 59 ms pulsar. Photon positions are digitized into $0.''1318$ pixels that oversample the on-axis point spread function (PSF) by a factor of 5. All HRC-I data were reprocessed and analyzed using the latest calibration files and software (CIAO 4.7/CALDB 4.6.5). Both observations were free of particle contamination flare events, yielding the exposure times reported in Table 1. For the timing analysis, photon arrival times were corrected to the solar system barycenter in barycentric dynamical time (TDB) using the *Chandra* measured coordinates given in Shevchuk et al. (2009).

2.2. Optical Observations

Although the nominal uncertainty in the aspect reconstruction for a typical *Chandra* observation is $0.''6$, we can refine the astrometry using optically identified sources. Potential reference sources in *Chandra* HRC-I and ACIS images of Calvera were discussed by Rutledge et al. (2008), Shevchuk et al. (2009), and Zane et al. (2011). We evaluated their relative merits for use in the HRC-I images and settled on CXOU J141259.4+791958, a faint X-ray source that is $2'$ south of Calvera, and has a relatively bright optical counterpart, $R = 18.6$ in the USNO B1.0 catalog (Monet et al. 2003). It is the only source close enough to Calvera for this purpose. We obtained R -band optical images of CXOU J141259.4+791958 using the MDM Observatory 2.4m Hiltner telescope on 2013 December 31, and an optical spectrum of it on 2014 February 9. The spectrum, obtained with OSMOS, the Ohio State Multi-Object Spectrograph, identifies CXOU J141259.4+791958 as a QSO with a broad Mg II emission line at $z = 1.229 \pm 0.002$, obviating the need to consider its own proper motion in the analysis. The images were used to refine its position in the USNO B1.0 reference frame to (J2000.0) R.A. = $14^h 12^m 59^s.436(72)$, decl. = $+79^\circ 19' 58.''81(20)$, in agreement with its optical position from Rutledge et al. (2008). The uncertainties quoted here are greater than the statistical errors, being simply the nominal $0.''2$ error in USNO positions, which we will consider a systematic uncertainty in the final positions (but not the proper motion, since that is a differential measurement).

2.3. X-ray Position and Proper Motion

The accuracy of the measured proper motion for Calvera is limited by the precision with which the coordinates of the reference source CXOU J141259.4+791958 can be determined in the 2.1 ks HRC-I image of 2007. This observation placed Calvera on the optical axis, with the reference source $2'$ off-axis having only eight photons (Rutledge et al. 2008). With this in mind, in planning for the proper motion measurement we placed the faint reference source on the optical axis instead to minimize the combined measured uncertainty. This yielded 175 counts for the reference source in the 30 ks observation of 2014, a number comparable to that obtained for Calvera in the 2007 image (see Table 1). In the following analysis we assume, as there is no evidence to the contrary, that the HRC-I focal plane is linear and the aspect reconstruction introduces no significant error in roll angle. The nominal roll uncertainty is $\approx 25''$, allowing a possible systematic

¹ http://cxc.harvard.edu/cal/Hrc/timing_200304.html

TABLE 2
POSITION MEASUREMENTS FOR CALVERA AND 1E 1207.4–5209

Epoch (year)	Reference Source (Optical)		Reference Source (X-ray)		Pulsar (Corrected)	
	R.A. (h m s)	Decl. ($^{\circ}$ ' ")	R.A. (h m s)	Decl. ($^{\circ}$ ' ")	R.A. (h m s)	Decl. ($^{\circ}$ ' ")
Calvera						
2007.134	14 12 59.436(72)	+79 19 58.81(20)	14 12 59.257(75)	+79 19 58.13(15)	14 12 55.918(76)	+79 22 04.09(15)
2014.250	14 12 59.436(72)	+79 19 58.81(20)	14 12 59.518(10)	+79 19 58.509(28)	14 12 55.815(11)	+79 22 03.697(30)
1E 1207.4–5209						
2003.991	12 09 41.915(22)	–52 24 55.94(20)	12 09 41.8660(41)	–52 24 56.098(59)	12 10 00.9186(41)	–52 26 28.347(59)
2013.962	12 09 41.915(22)	–52 24 55.94(20)	12 09 41.8752(41)	–52 24 55.973(59)	12 10 00.9053(41)	–52 26 28.260(59)

NOTE. — All coordinates are equinox J2000.0. X-ray positions of the reference sources are determined using the method described in Section 2.3. The pulsar coordinates are corrected by the difference between the optical and X-ray coordinates of the reference sources. Uncertainties on the last digits are given in parentheses.

TABLE 3
PROPER MOTION AND TIMING OF CALVERA

Parameter	Value ^a
Position and Proper Motion	
Epoch of position (MJD)	55,449.5
R.A. (J2000.0)	14 ^h 12 ^m 55 ^s .867(38)
Decl. (J2000.0)	+79°22′03″.895(76)
R.A. proper motion, $\mu_{\alpha} \cos \delta$	-40 ± 30 mas yr ^{–1}
Decl. proper motion, μ_{δ}	-56 ± 21 mas yr ^{–1}
Total proper motion, μ	69 ± 26 mas yr ^{–1}
Position angle of proper motion	$216^{\circ} \pm 23^{\circ}$
Tangential velocity ^b , $v_{\perp,c}$	86 ± 33 km s ^{–1}
Timing Solution	
Epoch of frequency (MJD TDB)	56,749.24
Span of timing solution (MJD)	55,074–56,749
Frequency, f	16.8922750(19) Hz
Frequency derivative, \dot{f}	$-9.15(15) \times 10^{-13}$ Hz s ^{–1}
Period, P	0.0591986574(67) s
Period derivative, \dot{P}	$3.207(53) \times 10^{-15}$
Surface dipole magnetic field, B_s	4.4×10^{11} G
Spin-down luminosity, \dot{E}	6.1×10^{35} erg s ^{–1}
Characteristic age, τ_c	290 kyr

^a Uncertainties in the last digits are given in parentheses.

^b Assuming $d = 0.3$ kpc and corrected to the LSR.

error of only 0″015 for a source 2′ off-axis². This is a factor of 10 smaller than the statistical error in the reference source position in ObsID 8508, so not a significant factor.

To determine the X-ray positions of Calvera and the reference source we use the “corrected centroid” method described in Gotthelf et al. (2013a). Briefly, this method is based on a simple centroid calculation for the source location that is corrected for the bias introduced in the measured coordinates due to any asymmetry in the PSF. This bias increases for sources farther from the optical axis and depends on the azimuthal orientation of the source in the focal plane. We consider this method preferable to forward fitting to a PSF model, for both faint and bright sources. A sophisticated method is not warranted for locating sources with few counts because it can introduce additional systematic errors, nor is it needed for highly significant sources (see Gotthelf et al.

2013a). To determine the PSF bias we produced a high statistic CHaRT/MARX simulation of each source at each epoch and compared their input coordinates to their centroid determined values. The relative offsets give the bias corrections to the astrophysical measurements.

The centroid measurements were iterated using the CIAO tool *dmstat* applied to photons extracted using a circular aperture whose radii are given in Table 1. In each case, the radii were chosen to enclose essentially all of the signal within that region of the PSF having a finite probability of producing a single count during the observation. To estimate the uncertainties in these X-ray coordinates we generated Monte Carlo images for each measured source by sampling the CHaRT/MARX simulated PSFs to match the observed source counts. From 10,000 realizations we accumulated centroid measurements to build up a distribution in right ascension and declination. To account for the observed background, in these simulations we included a random distribution of the estimated number of background photons within the source aperture. The resulting (Gaussian) width of the Monte Carlo centroids are found to be consistent with the expected “standard error” derived from the centroid measurement, $\approx \sigma/\sqrt{N}$, where N is the number of source counts in the aperture.

The final centroids of the reference source and Calvera in the two HRC-I images, corrected for the PSF bias, were then tied to the USNO B1.0 system using our optical astrometry described above. The resulting coordinates and their uncertainties are presented in Table 2. These values are used to compute the proper motion and its derived quantities (Table 3) by computing the change in the position of Calvera between epochs. The resulting proper motion is $\mu = 69 \pm 25$ mas yr^{–1}. Converting this to tangential velocity assuming $d = 0.3$ kpc gives $v_{\perp} = 98 \pm 35$ km s^{–1} relative to the Sun, or $v_{\perp,c} = 86 \pm 33$ km s^{–1} with respect to the local standard of rest (LSR) at the pulsar after correcting for Galactic rotation and peculiar solar motion. In Galactic coordinates, the position angle of proper motion is $+13^{\circ} \pm 23^{\circ}$ east of north ($+10^{\circ}$ in the LSR), i.e., nearly perpendicular to and away from the Galactic plane, given Calvera’s Galactic latitude of $b = +37^{\circ}$. Although the proper motion is less than a 3σ detection, its magnitude and direction will be used to place constraints on the birth location of Calvera.

² <http://cxc.harvard.edu/cal/ASPECT/roll.accuracy.html>

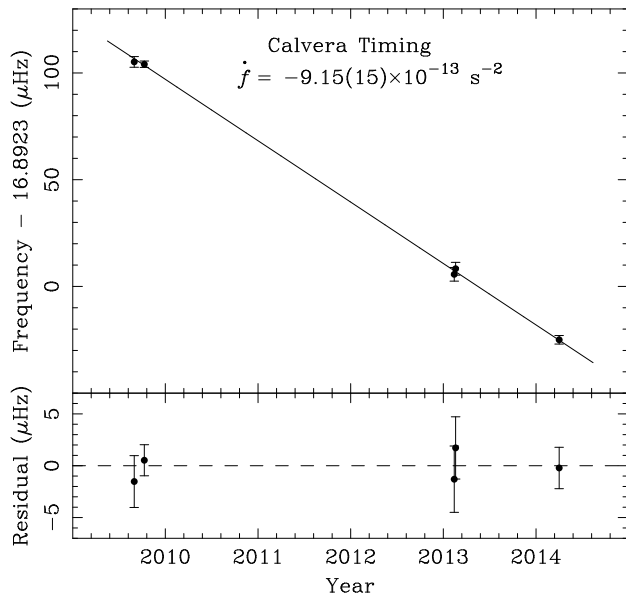


FIG. 1.— X-ray timing of Calvera, continued from Halpern et al. (2013). Points in 2009 are from the *XMM-Newton* EPIC pn in small window mode, points in 2013 are from *Chandra* ACIS S-3 in CC mode, and the point in 2014 is from *Chandra* HRC-I ObsID 15806 (Table 1).

2.4. X-ray Timing

Figure 1 show timing measurements of Calvera from 2009 and 2013 that were used by Halpern et al. (2013) to derive its spin parameters, together with the result of the 2014 *Chandra* HRC-I observation reported here that confirms and refines the spin-down rate. In order to optimize the signal-to-noise for a pulsar search in the HRC-I, 2760 counts were extracted from pulse invariant channels 1–400 in a $1''.6$ radius aperture. Applying the Rayleigh test to these photons yielded a peak power of 94.5 at a frequency of 16.892275(19) Hz. The pulsed fraction is $28 \pm 7\%$, similar to measurements with other instruments, although they cannot be compared directly because of the energy dependence of the pulsed fraction and the lack of energy resolution of the HRC. We note that the original 2.1 ks HRC-I observation of Calvera in 2007 had too few counts to detect its pulsation.

Table 3 lists the timing parameters of Calvera, but is not a phase ephemeris because the observations were too sparse to count cycles between them. The frequency derivative is derived from a linear χ^2 fit to the five frequency measurements as shown in Figure 1. Parameters derived from timing that are relevant to the evolution of young pulsars are the intermediate strength of the dipole magnetic, $B_s = 4.4 \times 10^{11}$ G, and the characteristic age of $\tau_c = 290$ kyr.

3. 1E 1207.4–5209

The 424 ms pulsar 1E 1207.4–5209 located in the SNR PKS 1209–51/52 = G296.5+10.0 (Helfand & Becker 1984; Zavlin et al. 2000; Pavlov et al. 2002) was the first isolated pulsar to display strong absorption lines in its X-ray spectrum (Mereghetti et al. 2002; Sanwal et al. 2002; Bignami et al. 2003; De Luca et al. 2004). This series of equally spaced lines, at 0.7, 1.4, and 2.1 keV, has been interpreted as either atomic transi-

tions in a strong magnetic field (Hailey & Mori 2002; Mori & Hailey 2006), or electron cyclotron resonant features in a weaker field, $\approx 8 \times 10^{10}$ G (Bignami et al. 2003; De Luca et al. 2004; Gotthelf & Halpern 2007; Halpern & Gotthelf 2011). Like the other CCO pulsars, the spin-down rate of 1E 1207.4–5209, $\dot{P} = 2.2 \times 10^{-17}$, is unusually small for its youth, implying a surface magnetic field of only $B_s = 9.8 \times 10^{10}$ G in the vacuum dipole model. This field is 1–2 orders of magnitude smaller than that associated with a typical young rotation-powered pulsar, but notably favors the electron-cyclotron resonance interpretation for the absorption features, reasonably predicting the measured line energies.

De Luca et al. (2011) pointed out that, considering the bilateral symmetry of PKS 1209–51/52, 1E 1207.4–5209 appears to lie $8'$ to the north east of the geometrical center of the SNR, so a large proper motion of the pulsar is expected. Assuming an age of 7000 years (Roger et al. 1988) and a distance of 2 kpc (Giacani et al. 2000), De Luca et al. (2011) proposed that $\mu \sim 70$ mas yr^{-1} . Such motion would be easily detected by *Chandra* between the two archival HRC-I observations separated by 10 years. The corresponding tangential velocity would be high, ~ 640 km s^{-1} , much larger than the average of $\bar{v}_{\perp,c} = 246 \pm 22$ km s^{-1} for 121 ordinary (non-recycled) pulsars, or $\bar{v}_{\perp,c} = 307 \pm 47$ km s^{-1} for 46 pulsars whose characteristic ages are < 3 Myr (Hobbs et al. 2005). Furthermore, $\mu = 70$ mas yr^{-1} would contribute a significant kinematic term \dot{P}_k to the period derivative via the Shklovskii (1970) effect, given by

$$\dot{P}_k = \frac{\mu^2 P d}{c} = \frac{v_{\perp}^2 P}{dc} \approx 9.4 \times 10^{-18}, \quad (1)$$

fully $\sim 40\%$ of the observed value. This fraction would have to be subtracted from \dot{P} to derive the magnetic field. This raises the possibility that CCOs as a class have large space velocities since PSR J0821–4300 in Puppis A was measured to have $v_{\perp,c} = 629 \pm 126$ km s^{-1} using *Chandra* (Becker et al. 2012; Gotthelf et al. 2013a). (For PSR J0821–4300 the kinematic contribution is 24% of \dot{P} .)

3.1. X-Ray Observations and Analysis

1E 1207.4–5209 was observed with the HRC-I twice, initially on 2003 December 28 (ObsID 4592; P.I. Murray) to provide an initial epoch for a proper motion study, and again 10 years later on 2013 December 18 to measure the proper motion (ObsID 15291; P.I. Predehl). An observation log is presented in Table 1. These data are free of particle contamination from solar flare events, yielding exposure times of 49.71 ks and 35.88 ks, respectively. In both images 1E 1207.4–5209 was placed at the nominal on-axis location resulting in very accurate centroid measurements with negligible PSF bias.

In deep *XMM-Newton* images, several X-ray sources with optical counterparts lie near 1E 1207.4–5209 (Novara et al. 2006, 2009), but the less sensitive HRC-I detects a small subset of these. For a reference source in the proper motion analysis we choose the brightest X-ray source close to 1E 1207.4–5209, #338 of Novara et al. (2009), which lies $3.3'$ away and which they classify as a QSO based on its X-ray and optical properties. It

TABLE 4
EPHEMERIS OF 1E 1207.4–5209

Parameter	Value ^a
Position and Proper Motion	
Epoch of position (MJD)	54,823.0
R.A. (J2000.0)	12 ^h 10 ^m 00. ^s 9126(29)
Decl. (J2000.0)	−52°26′28″303(42)
R.A. proper motion, $\mu_\alpha \cos \delta$	−12 ± 5 mas yr ^{−1}
Decl. proper motion, μ_δ	9 ± 8 mas yr ^{−1}
Total proper motion, μ	15 ± 7 mas yr ^{−1}
Position angle of proper motion	305° ± 29°
Tangential velocity ^b , $v_{\perp,c}$	< 180 km s ^{−1}
Timing Solution	
Epoch of ephemeris (MJD TDB) ^c	53,562.0000006
Span of ephemeris (MJD)	51,549–56,829
R.A. (J2000.0)	12 ^h 10 ^m 00. ^s .91
Decl. (J2000.0)	−52°26′28″.4
Frequency, f	2.357763502866(65) Hz
Frequency derivative, \dot{f}	−1.2398(83) × 10 ^{−16} Hz s ^{−1}
Period, P	0.424130748815(12) s
Period derivative, \dot{P}	2.230(14) × 10 ^{−17}
Surface dipole magnetic field, B_s	9.8 × 10 ¹⁰ G
Spin-down luminosity, \dot{E}	1.2 × 10 ³¹ erg s ^{−1}
Characteristic age, τ_c	301 Myr

^a Uncertainties in the last digits are given in parentheses.

^b Assuming $d = 2$ kpc and corrected to the LSR of the pulsar

^c Epoch of minimum of the pulse profile, phase zero in Figure 13 of Gotthelf et al. (2013a).

is cataloged as USNO B1.0 0375-0393687, with position listed in Table 2. A second source, #404 of Novara et al. (2009), is 2′5 from 1E 1207.4–5209, but it is ~ 4 times fainter than #338 and is identified with a 15th magnitude K star that has an uncertain proper motion, cataloged as 188-075241 in the UCAC4 (Zacharias et al. 2013), so we do not use it. As described above, we do not expect a significant error in proper motion as a result of using only one reference source. Incorporating weaker sources further off-axis does not improve the astrometry, since their PSFs are worse. The two observations were taken at nearly the same roll angle (see Table 1). Four out of the five guide stars used in the aspect solution were identical between the two observations, so any systematic error in their positions should cancel in the proper motion analysis.

Using the method described for Calvera, we measure an insignificant total proper motion of 15 ± 7 mas yr^{−1} for 1E 1207.4–5209; results are given in Table 4. Converting this uncertain value to tangential velocity assuming $d = 2$ kpc gives 142 km s^{−1} relative to the Sun, or 93 km s^{−1} at the LSR of the pulsar after correcting for Galactic rotation and peculiar solar motion. However, the substantial uncertainty on proper motion and position angle render the correction so variable that we quote only an upper limit of $v_{\perp,c} < 180$ km s^{−1} in Table 4.

We have also completed a long-term timing campaign on 1E 1207.4–5209 and present the final results here, including three new *Chandra* observations using ACIS-S3 in CC-mode that extend our previous study (Gotthelf et al. 2013a) by 1.6 years. A log of the new observations is given in Table 5; we refer to the earlier work (Halpern & Gotthelf 2011; Gotthelf et al. 2013a) for details of the previous observations and the methods used

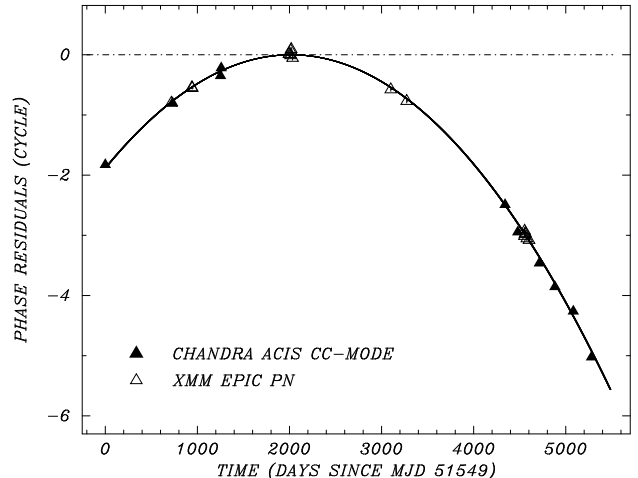


FIG. 2.— Pulse-phase residuals from the linear term (dash-dot line) of the phase ephemeris of 1E 1207.4–5209, continued from Gotthelf et al. (2013a). All timing data obtained by *XMM-Newton* and *Chandra* are included, with the three new observations listed in Table 5. The quadratic term (solid line) corresponds to the uniquely determined period derivative spanning the years 2000–2014. The error bars are generally smaller than the symbol size.

for timing analysis.

Our final ephemeris for 1E 1207.4–5209 in Table 4 spans the years 2000–2014. In view of the insignificant proper motion measurement, we performed the timing at a fixed source position given in the bottom part of Table 4. The prior ephemeris predicted well the pulse phases at the new epochs, allowing us to extend the phase-connect timing solution with improved precision. 1E 1207.4–5209 is a stable rotator with imperceptible timing noise or glitch activity, which is not unexpected for a such low \dot{E} pulsar. The phase residuals from a linear ephemeris are shown in Figure 2.

4. DISCUSSION AND CONCLUSIONS

4.1. Calvera

Although hundreds of radio pulsar proper motions have been measured using timing or interferometry (Hobbs et al. 2005), Calvera is the sixth NS for which significant proper motion has been measured only in X-rays with *Chandra*. The others are PSR J0821–4300 in Puppis A (Becker et al. 2012; Gotthelf et al. 2013a), the nearby isolated NS RX J1308.6+2127 (Motch et al. 2009), and the γ -ray pulsars J1809–2332 (van Etten et al. 2012), J0357+3204 (De Luca et al. 2013), and J1741–2054 (Auchettl et al. 2015).

Calvera is the most extreme example of a “young” pulsar at high Galactic latitude, $b = +37^\circ$. It presents an interesting problem because, if in the Galactic halo, it was either born there or it was ejected from the disk at high velocity, $v \approx 1000 z_{0.3}$ km s^{−1}, where $z_{0.3}$ is its height above the disk in units of 0.3 kpc. This is near the extreme limit of observed velocities of pulsars (Hobbs et al. 2005). Ejection perpendicular to the disk requires a proper motion $\mu \sim \sin b \cos b / \tau_c = 340$ mas yr^{−1} to have reached its present latitude in $\tau_c = 290$ kyr. Since the true age of a short-period pulsar could be less than its characteristic age, the proper motion could have been

TABLE 5
LOG OF NEW X-RAY TIMING OBSERVATIONS OF 1E 1207.4–5209

Mission	Instr/Mode	ObsID	Date (UT)	Exposure (ks)	Start Epoch (MJD)	Frequency ^a (Hz)	Z_1^2
<i>Chandra</i>	ACIS-S3/CC	14203	2013 May 19	33.2	56,431.195	2.3577627(37)	46.63
<i>Chandra</i>	ACIS-S3/CC	14201	2013 Dec 04	33.2	56,630.920	2.3577548(56)	19.57
<i>Chandra</i>	ACIS-S3/CC	14204	2014 Jun 20	33.2	56,828.961	2.3577660(61)	20.86

^a Barycentric frequency derived from a Z_1^2 test. Uncertainty on the last digits is given in parentheses for the 1σ confidence interval.

even larger.

We were anticipating a large proper motion, but since only $\sim 70 \text{ mas yr}^{-1}$ is observed, Calvera has moved only $\sim 5.6^\circ$ in 290 kyr. Even though its proper motion vector is away from the Galactic plane, $+13^\circ$ east of north, its high Galactic latitude could be due more to the proximity of its birth. If at a distance of $\lesssim 0.3 \text{ kpc}$, its tangential velocity is $\lesssim 120 \text{ km s}^{-1}$, corresponding to a displacement of $\lesssim 35 \text{ pc}$ in 290 kyr. It could have been born in the young disk of scale height $\approx 125 \text{ pc}$.

Several studies of isolated NSs with X-ray or optical proper motion measurements and distance estimates have identified possible birth locations in nearby OB associations (e.g., Walter 2001; Kaplan et al. 2007; Motch et al. 2009; Tetzlaff et al. 2010). These NSs had precise measurements compared to Calvera's, which has only a marginally significant proper motion, an uncertain direction, and an unknown distance. Therefore, we do not perform the detailed analyses of those studies. However, we considered several of the nearest OB associations in Cepheus, namely Cep OB2, OB3, OB4, and OB6, which are within an angular distance $\Delta = 30^\circ - 40^\circ$ of Calvera and lie in or near the cone of uncertainty of its motion. Cep OB6 is at a distance of $r \approx 270 \text{ pc}$, and the others are in the range $r \approx 615 - 845 \text{ pc}$ (de Zeeuw et al. 1999).

Because of the proximity of these clusters and the youth of Calvera, we may with good accuracy neglect differential rotation and acceleration in the Galactic potential, and evaluate the plausibility of the Cep OB associations as birth sites by using a straight trajectory and simple trigonometry. Assume that τ_c is the true age of the NS, which has travelled an angular distance Δ from a hypothetical birth site at a distance r and is now observed to have proper motion μ . Its present distance d and space velocity v are then specified by the two relations

$$d = \frac{r \sin \Delta}{\mu \tau_c} \quad (2)$$

and

$$v = \frac{1}{\tau_c} \sqrt{(r - d \cos \Delta)^2 + (d \sin \Delta)^2}. \quad (3)$$

We applied Equations (2) and (3) to the locations of the Cep OB associations, and find no reasonable solutions, defined as having $v \leq 2000 \text{ km s}^{-1}$, even allowing a factor of 2 uncertainty in μ . With its small proper motion and young age, Calvera would need an extremely large radial component of velocity to have come from an OB association in the Galactic plane. The difficulty is compounded if the true age is less than τ_c , as is likely for a short-period, young pulsar like Calvera.

One may also ask if it is possible for Calvera to have been born in one of the young local associations within $r < 60 \text{ pc}$, such as Tuc-Hor or β Pic-Cap (Fernández et al. 2008), which are $\sim 10 - 20 \text{ Myr}$ old and extend to large, negative Galactic latitudes. While the kinematics would allow this, most such trajectories would also require a high space velocity. Furthermore, we consider it likely that $d > 200 \text{ pc}$ because Calvera's X-ray measured column density (Zane et al. 2011) is consistent with the total Galactic 21 cm value in its direction, which argues that it is not within the local bubble. Imposing $d > 200 \text{ pc}$ and $r < 60 \text{ pc}$ would require $v > 580 \text{ km s}^{-1}$, with most trajectories having v much larger than that.

A small distance to Calvera would imply that it is extremely underluminous in γ -rays. Halpern et al. (2013) placed an upper limit of $7.4 \times 10^{30} d_{0.3}^2 \text{ erg s}^{-1}$ (assumed isotropic) on its $> 100 \text{ MeV}$ luminosity in *Fermi*, which is a factor of 10^3 or more below typical pulsars of the same \dot{E} (Abdo et al. 2013). Romani et al. (2011) derived several γ -ray upper limits for pulsars, but none were this weak. They favored an interpretation in which an aligned rotator would beam outer-gap emission away from the observer. But Calvera is not likely to be an aligned rotator given its large X-ray pulsed fraction. Therefore, such a small distance would imply a new constraint on models of radio and γ -ray beaming, as Calvera is silent in both bands.

Alternatively, a distance up to $\sim 2 \text{ kpc}$ for Calvera is allowed by either the surface area of the thermal emission, or the conversion of rotational energy to luminosity. It is entirely possible that some of its thermal emission is due to polar cap heating by backflowing magnetospheric particles. A typical ratio $L_x/\dot{E} \sim 10^{-3}$ attributed to this process is seen in thermally emitting millisecond pulsars. Calvera's bolometric X-ray luminosity is $\sim 5 \times 10^{32} d_2^2 \text{ erg s}^{-1}$, consistent with the typical $L_x/\dot{E} \sim 10^{-3}$ at $d = 2 \text{ kpc}$. At such distance, Calvera must have been born in the halo, possibly of a runaway O or B star progenitor from the disk. In that case its proper motion could have been oriented randomly after the supernova kick.

Because of its intermediate strength magnetic field, Calvera is of particular interest as a possible prototype CCO descendant with an emerging magnetic field. Its actual age could be much less than its present characteristic age. The X-ray spectrum of Calvera is best fitted by a two temperature, blackbody or hydrogen atmosphere model, with kT in the range $0.1 - 0.25 \text{ keV}$ (Shevchuk et al. 2009; Zane et al. 2011). However, it is difficult to characterize its thermal age using theoretical cooling curves because they are highly uncertain, and also because Calvera's X-ray emitting hot spot(s) proba-

bly do not represent the full surface area of the NS. Thus, the distance and age of Calvera both remain uncertain by an order of magnitude, and its potential to illuminate the evolution of CCOs is yet to be fully realized.

4.2. 1E 1207.4–5209

The insignificant proper motion of 1E 1207.4–5209, 15 ± 7 mas yr⁻¹ is much smaller than the ~ 70 mas yr⁻¹ predicted by De Luca et al. (2011) based on the separation of the NS from the apparent center of PKS 1209–51/52, and it does not point toward the north east, away from the center as would be expected. This shows that the shape of the SNR is not a reliable indicator of the location of its kinematic (expansion) center. The kinematics of the remnant have not in fact been measured. Roger et al. (1988) and De Luca et al. (2011) noted that the eastern side of the SNR has a smaller radius of curvature than the western side, which could be used to argue that the supernova occurred further to the east, closer to the present position of the NS.

The small proper motion of 1E 1207.4–5209 also means that the kinematic contribution to its period derivative is negligible, $\dot{P}_k \sim 4.6 \times 10^{-19}$ from Equation (1), compared to the observed $\dot{P} = 2.23 \times 10^{-17}$, so its

spin-down magnetic field does not have to be modified.

This result also suggests that CCOs do not receive larger kick velocities than average. Although PSR J0821–4300 in Puppis A has an unusually large tangential velocity of ≈ 630 km s⁻¹, it is balanced by the smaller than average velocity of 1E 1207.4–5209, < 180 km s⁻¹. The only other CCO that has a velocity estimate, which is reliable as it refers to the kinematic center of its SNR, is the NS in Cas A, for which Thorstensen et al. (2001) and Fesen et al. (2006) find $v_{\perp} \approx 350$ km s⁻¹, close to the average of young pulsars. This implies that, in the theory of prompt fall-back and field burial onto CCOs, the NS kick velocity is not an important factor in determining how much mass is accreted.

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